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MAGIC OBSERVATIONS OF VERY HIGH ENERGY γ-RAYS FROM HESS J1813-178

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ABSTRACT

Recently, the HESS collaboration has reported the detection of γ-ray emission above a few hundred GeV from eight new sources located close to the Galactic Plane. The source HESS J1813-178 has sparked particular interest, as subsequent radio observations imply an association with SNR G12.82-0.02. Triggered by the detection in VHE γ-rays, a positionally coincident source has also been found in INTEGRAL and ASCA data. In this *Letter* we present MAGIC observations of HESS J1813-178, resulting in the detection of a differential γ-ray flux consistent with a hard-slope power law, described as $\mathrm{d}N_\gamma/(\mathrm{d}A\mathrm{d}t\mathrm{d}E) = (3.3 \pm 0.5) \times 10^{-12} (E/\mathrm{TeV})^{-2.1\pm0.2}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}\mathrm{TeV}^{-1}$. We briefly discuss the observational technique used, the procedure implemented for the data analysis, and put this detection in the perspective of multifrequency observations.

Subject headings: gamma rays: observations, supernova remnants: individual (HESS J 1817-178, G12.82-0.02), acceleration of particles

1. INTRODUCTION

In the Galactic Plane scan performed with the HESS Cherenkov array in 2004, with a flux sensitivity of 3% Crab units for γ-rays above 100 GeV, eight sources were discovered (Aharonian et al. 2005a,b). One of the newly detected γ-ray sources was HESS J1813-178. At the beginning, HESS J1813-178 could not be identified and was assumed to be a "dark particle accelerator", without reported counterparts at lower frequencies.

Since the original discovery, HESS J1813-178 has been associated with the supernova remnant SNR G12.82-0.02 (Ubertini et al. 2005; Brogan et al. 2005; Helfand et al. 2005). One may still not exclude this coincidence being the result of just a chance association. Aharonian et al. (2005a) state a probability of (6%) that one of their new sources is by chance spatially consistent with a SNR. Nevertheless, the properties of SNR G12.82-0.02, the multifrequency spectral energy distribution, and the flux and spectrum of the high energy γ-rays detected from this direction appear to be consistent with a SNR origin.

HESS J1813-178 has been found to be nearly point like ($\sigma_{\mathrm{source}} = 2.2'$) by Aharonian et al. (2005b). Given the size of the SNR, the angular resolution of the HESS telescope, and the depth of the observations, the source size does not rule out a possible shell origin. The γ-ray source lies at $10'$ from the center of the radio source W33. This patch of the sky is highly obscured and has indications of being a recent star formation region (Churchwell 1990).

In this *Letter* we present Major Atmospheric Gamma Imaging Cherenkov telescope (MAGIC) observations of HESS J1813-178. We briefly discuss the observational technique used and the procedure implemented for the data analysis. We derive a high energy γ-ray spectrum of the source, and analyze it in the perspective of multifrequency observations.

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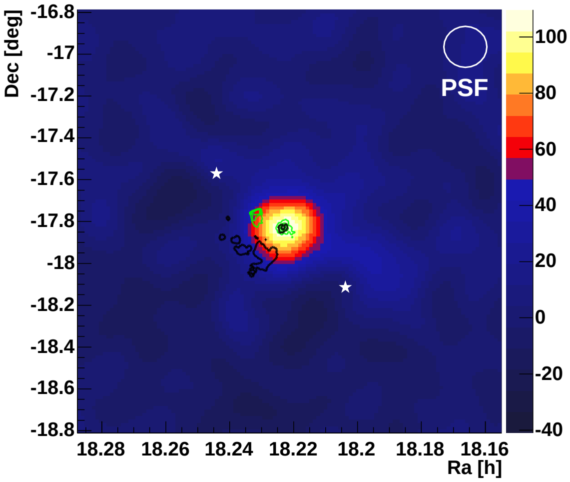

FIG. 1.— Sky map of γ-ray candidate events (background subtracted) in the directions of HESS J1813-178 for SIZE $\geq$ 600 ph. el. (corresponding to an energy threshold of about 1 TeV). Overlayed are contours of 90 cm VLA radio (black) and ASCA X-ray data (green) from Brogan et al. (2005). The two white stars denote the tracking positions W1,W2 in the wobble mode.

2. OBSERVATIONS

MAGIC (see e.g., Baixeras et al. (2004); Cortina et al. (2005)) is currently the largest single dish Imaging Air Cherenkov Telescope (IACT) in operation. Located on the Canary Island La Palma (28.8°N, 17.8°W, 2200 m a.s.l), the telescope has a 17-m diameter tessellated parabolic mirror, supported by a light weight carbon fiber frame. It is equipped with a high efficiency 576-pixel 3.5° field-of-view photomultiplier camera. The analogue signals are transported via optical fibers to the trigger electronics and are read out by a 300 MSamples/s FADC system.

At La Palma, HESS J1813-178 culminates at about 47° zenith angle (ZA). The large ZA implies a high energy threshold of about 400 GeV for MAGIC observations. It also provides a large effective collection area (see e.g. Konopelko et al. (1999)). The sky region around the location of HESS J1813-178 has a relatively high and non-uniform level of light. Within a distance of 1° from HESS J1813-178, there are no stars brighter than 8^{th} magnitude, with the star field being brighter in the region SW of the source.

The MAGIC observations were carried out in the false-source tracking (wobble) mode (Fomin et al. 1994). The sky directions (W1, W2) to be tracked are chosen such that in the camera the sky field relative to the source position is similar to the sky field relative to the mirror source position (anti-source position). The source direction is in both cases 0.4° offset from the camera center. In Fig. 1 these two tracking positions are shown by white stars. During wobble mode data taking, 50% of the data is taken at W1 and 50% at W2, switching (wobbling) between the 2 directions every 30 minutes. This observation mode allowed a reliable background estimation least affected by the large ZA and inhomogeneous star field.

3. DATA ANALYSIS

HESS J1813-178 was observed for a total of 25 hours in the period June-July 2005 (ZA $\leq 52^{\circ}$). About 15 million triggers have been recorded. The calibration of the raw data of the MAGIC camera is explained in Gaug et al. (2005). Image cleaning tail cuts were applied: Pixels are only considered

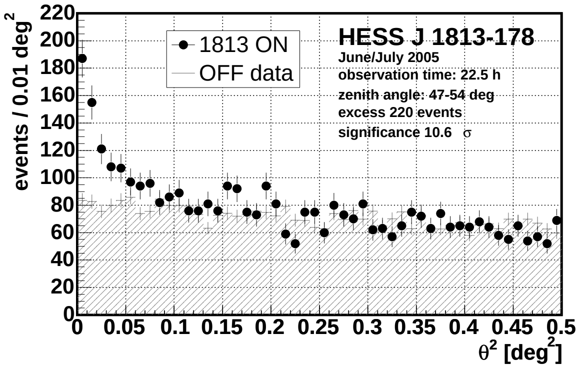

FIG. 2.— Distributions of θ^2 values for the source and anti-source, see text, for SIZE $\geq$ 600 ph. el. (corresponding to an energy threshold of about 1 TeV).

to be part of the image if their reconstructed charge signal is larger than 10 photo electrons (ph.el.) (core pixels) or if their charge is larger than 5 ph. el. and they have at least one neighboring core pixel. These tail cuts are accordingly scaled for the larger outer pixels of the MAGIC camera. The camera images are characterized by image parameters (Hillas 1985). After the image cleaning and rejection of broken runs about 10 million events remained for further analysis. These data were processed for γ/hadron separation, in a similar way as described in Fegan (1997).

In this analysis, the Random Forest method (see Bock et al. (2004) for a detailed description) was applied for the γ/hadron separation and the energy estimation. For the training of the Random Forest a sample of Monte Carlo (MC) generated γ-showers was used to represent the γ-rays and a randomly chosen sub-set of the measured data was used to represent the background. The MC γ-showers were generated between 47° and 54° ZA with energies between 10 GeV and 30 TeV. The spectral index of the generated differential spectrum $dN_{\gamma}/dE \sim E^{\Gamma}$ was chosen as $\Gamma = -2.6$, in agreement with the MAGIC-observed energy spectrum of the Crab nebula (Wagner et al. 2005).[22] The source-position independent image parameters SIZE, WIDTH, LENGTH, CONC (Hillas 1985) and the third moment along the major image axis, as well as the source-position dependent parameter DIST (Hillas 1985), were selected to parameterize the shower images. After the training, the Random Forest method allows to calculate for every event a parameter, dubbed hadronness, which is a measure of the probability that the event belongs to the background. The γ-sample is defined by selecting showers with a hadronness below a specified value. An independent sample of MC γ-showers was used to determine the efficiency of the applied cuts.

For each event, its original sky position is determined by using the DISP-method (Fomin et al. 1994; Lessard et al. 2001). At this stage only source independent image parameters are used in the RF training. Figure 1 shows the sky map of γ-ray candidate events (background subtracted) from the direction of HESS J1813-178. It is smoothed with a two-dimensional Gaussian with a standard deviation of 0.1°. To provide a good angular resolution a tight hadronness cut and a lower SIZE cut of 600 ph. el. has been applied. The SIZE cut corresponds

[22] In order to develop and verify the analysis at high zenith angles, Crab data in the interesting ZA range around 50° were taken in January 2005. From that sample, we determined the Crab energy spectrum and found it to be consistent with other existing measurements (see Fig. 3, upper curve).

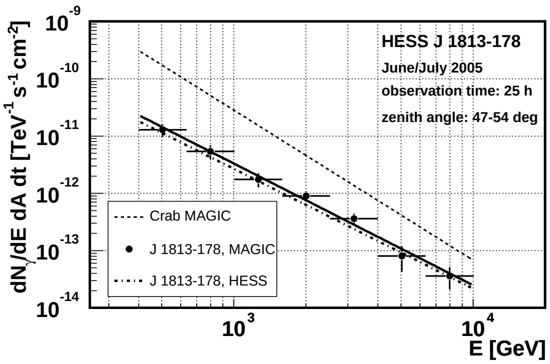

FIG. 3.— Reconstructed VHE γ-ray spectrum of HESS J1813-178. The spectral index is -2.1 ± 0.2 and the integral flux above 400 GeV is about 8% of the Crab nebula (statistical errors only). The dashed line shows the spectrum of the Crab nebula as measured by MAGIC (Wagner et al. 2005). The dot-dashed line shows the results of the HESS collaboration (Aharonian et al. 2005b).

to an energy threshold of about 1 TeV. The sky map is overlayed with contours of 90 cm VLA radio and ASCA X-ray data from Brogan et al. (2005). The excess is centered at (RA, DEC)=($18^{\rm h}13^{\rm m}27^{\rm s}$, -17°48′40″) and coincides well with the position of SNR G12.82-0.02. The systematic pointing uncertainty is estimated to be 2′ (for description of the MAGIC telescope drive system see Bretz et al. (2003)) and might in future be greatly reduced with the MAGIC starfield monitor (Riegel et al. 2005). Apart from the main excess coincident with HESS J1813-178 there are no other significant excesses present.

Figure 2 shows the distribution of the squared angular distance, θ^2, between the reconstructed shower direction and the nominal object position. The observed excess in the direction of HESS J1813-178 has a significance of 10.6 standard deviations (according to equation 17 of Li&Ma (1983)). Within errors the source position and the flux level are compatible with the measurement of HESS (Aharonian et al. 2005b).

For the determination of the energy spectrum, the RF was trained including the source dependent image parameter DIST with respect to the nominal excess position. A loose cut on the hadronness was used. Above the low energy turn-on, the cut efficiency reaches about 70% corresponding to an effective collection area for γ-ray showers of about 180000 m^2. Figure 3 shows the reconstructed very high energy γ-ray spectrum of HESS J1813-178 after the unfolding with the instrumental energy resolution. The measured spectral points are fit by a simple power law spectrum, taking the full instrumental energy resolution into account as described in Mizobuchi et al. (2005). The result is given by ($\chi^2/\mathrm{n.d.f} = 5.3/5$):

$$\frac{\mathrm{d}N_\gamma}{\mathrm{d}A\mathrm{d}t\mathrm{d}E} = (3.3 \pm 0.5) \times 10^{-12} (E/\mathrm{TeV})^{-2.1 \pm 0.2} \\ \mathrm{cm}^{-2}\mathrm{s}^{-1}\mathrm{TeV}^{-1}.$$

The quoted errors (1σ) are purely statistical. The systematic error is estimated to be 35% in the flux level determination and 0.2 in the spectral index. Within errors the flux is steady in the time scales explored within these observations (weeks), as well as in the year-long time-span between the MAGIC and HESS pointings.

4. DISCUSSION

Shortly after the discovery of HESS J1813-178, X-ray emission was found in ASCA data coming from the source

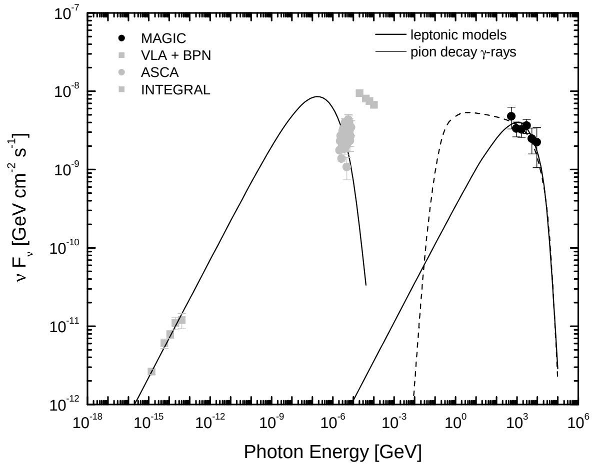

FIG. 4.— Leptonic and hadronic models for the J1813-178 data. Details are given in the text. Radio data is from VLA, Bonn, Parkes, and Nobeyama observatories (Brogan et al. 2005), X-ray and hard X-ray data are from ASCA and INTEGRAL (Ubertini et al. 2005, Brogan et al. 2005).

AX J1813-178 (a.k.a. AGPS 273.4-17.8), Brogan et al. (2005), also Ubertini et al. (2005). X-ray emission detected by ASCA is predominantly non-thermal, and compatible with that expected from a PWN or a SNR shell. X-ray pulsed emission has not been detected, but the quality and amount of the data does not imply strong constraints (Brogan et al. 2005). Statistically, X-ray data are not good enough to unambiguously separate a pure power law from power law + thermal contribution either. However, in both cases, none of the two component fits yield a significantly different absorbing column density or photon index when compared with a single power law fit (Brogan et al. 2005). Data analysis from the INTEGRAL satellite also showed a soft and luminous source at the same location, in the 20-100 keV range (Ubertini et al. 2005).

Simultaneously with this X-ray match, HESS J1813-178 was also found as a non-thermal source in radio data, using observations with VLA (90 and 20 cm), Bonn (3 cm), Parkes (6 cm), and Nobeyama (3 cm) telescopes (Brogan et al. 2005; Helfand et al. 2005). These groups discovered a shell-type supernova remnant (SNR G12.8-0.0) with a section of the shell coinciding with HESS J1813-178. The radio spectral index was found to be -0.48 $\pm$ 0.03. There are no known radio pulsars detected at the HESS J1813-178 position (Manchester et al. 2005).

Brogan et al. (2005) conclude that SNR G12.8-0.0 should lie at or beyond the distance of W33, ~ 4 kpc. They have derived a high column density of $N_H \sim 10^{23}$ cm^{-2} from the ASCA data which suggests a significant source of absorption in the foreground.

The multi-wavelength emission coming from the direction of HESS J1813-178 is shown in Fig. 4, including the new MAGIC data at high energies. We have compared hadronic (neutral pion decay) and leptonic (inverse Compton) emission models with the high energy γ-ray data, for a review see Torres et al. (2003). In the case of hadronic models, the observed γ-ray luminosity (2.5×10^{34} erg s^{-1} between 0.4 - 6 TeV, at 4 kpc) implies that the required density of matter is ~ 6 cm^{-3}. The γ-ray production region is presumed to be the whole SNR volume. An acceleration efficiency of

hadrons of the order of 3% and a supernova power of 10^{51} erg was assumed. Therefore, relativistic hadrons need only about 2 $M_\odot$ of target mass inside the SNR volume ($\sim$1.5 pc radius at 4 kpc distance) in order to be consistent with the observed luminosity. Alternatively, the target mass for the cosmic ray spectrum can be provided by a small cloud of a few solar masses located in a region close to the SNR shell. For the model shown in Fig. 4, we have assumed that the proton distribution is described by $\mathrm{d}N_p/(\mathrm{d}V\mathrm{d}E) = A_p(E/\mathrm{GeV})^{-\alpha}\exp\left(-E/E_{\max}\right)\ \mathrm{GeV}^{-1}\mathrm{cm}^{-3}$ where A_p is a dimensionless normalization constant. We found that $\alpha = 2.1$ and $E_{\max} = 100$ TeV is a good fit to the data, and that the normalization constant is such that the amount of supernova explosion energy converted into relativistic cosmic rays needs not to be more than a few percent to agree with MAGIC observations.

For leptonic models, we have assumed a similarly described distribution of relativistic electrons $\mathrm{d}N_e/(\mathrm{d}V\mathrm{d}E) = A_e(E/\mathrm{GeV})^{-\alpha_e}\exp\left(-E/E_{\max,\mathrm{e}}\right)\ \mathrm{GeV}^{-1}\mathrm{cm}^{-3}$. We found that several different inverse Compton models produce reasonable good fits at high energies, e.g. $\alpha_e = 2.0$ and $E_{\max,\mathrm{e}} = 20$ TeV; and $\alpha_e = 2.1$ and 2.2 and $E_{\max,\mathrm{e}} = 30$ TeV, all having their energetics at ease with the energy assumed to be released by the supernova explosion. The source of target photons for these models was assumed to be the cosmic microwave background. The radio spectrum at lower energies is fitted best by a slope of $\alpha_e = 2.0$. It is computed as synchrotron emission of the same electron population. In the model shown in Fig. 4, a magnetic filling fraction of about 20%, a magnetic field of 10 μG and $E_{\max,\mathrm{e}} = 20$ TeV and $\alpha_e = 2.0$ have been adopted. This model is similar to one of the models presented by Brogan et al. (2005) (blue line in their Fig. 3, $E_{\max,\mathrm{e}} = 30$, $\alpha_e = 2.0$), without yet having a high energy γ-ray spectrum. The soft X-ray data (ASCA) plotted correspond to those shown by Brogan et al. (2005) (black data points in their Fig. 3). Our model, as well as Brogan et al.'s, is in rough agreement with MAGIC data, radio and roughly also with the X-ray data, even if the spectral behaviour in the ASCA energy range (the slope) is somewhat different. That is, we have priviledged the radio data in fitting this SED as an example, a better X-ray fitting could be obtained at the expense of a worse radio one. It is worth noticing that the hard X-ray data of INTEGRAL (Ubertini et al. 2005) cannot be fitted well with the same electron population that is assumed to produce higher and lower energy photons. Nevertheless, as one can see in Fig. 2 of (Ubertini et al. 2005), the ASCA, MAGIC and HESS sources match spatially well, while the INTEGRAL/IBIS source is spatially only marginally compatible with them. Further multi-frequency observations in the x-ray and hard x-ray regime are needed to obtain definite conclusions up to what level the leptonic models need two electron populations.

5. CONCLUDING REMARKS

The detection of HESS J1813-178 using the MAGIC Telescope confirms a new very high-energy γ-ray source in the Galactic Plane. A reasonably large data set was collected from observations at large zenith angles to infer the spectrum of this source up to energies of about 10 TeV. Between 400 GeV and 10 TeV the differential energy spectrum can be fitted with a power law of slope $\Gamma = -2.1 \pm 0.2$. These data can be used to cross-calibrate HESS and MAGIC, their independent observations show satisfactory agreement.

Multifrequency data in the radio, X-ray, and γ-ray band imply a connection between HESS J1813-178 and SNR G12.82-0.02 (Helfand et al. 2005; Ubertini et al. 2005; Brogan et al. 2005). Generally, hard γ-ray spectra are expected from SNRs due to Fermi acceleration of cosmic rays (Ginzburg & Syrovatskii 1964; Torres et al. 2003). The hard spectrum determined for HESS J1813-178 may be a further hint for its association with the SNR G12.82-0.02.

Present data are not sufficient to discriminate between existing models for different acceleration mechanisms. Future observations at lower energies with improved gamma-ray telescopes and/or the GLAST satellite will undoubtedly permit to shed more light on the existing leptonic and hadronic models. Decisive information concerning hadronic acceleration mechanisms is also likely to come from future neutrino telescopes like IceCube (Ahrens et al. 2004).

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